Catastrophic Landslides – Quantifying the Link to Landscape Evolution

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Abstract.
Rock avalanches are considered a high magnitude, relatively low frequency event in the high mountains. Rock avalanches are triggered by a number of forcing factors, rainfall, seismic acceleration, and more debatably, through the longer term the action of glacial de-buttressing, and also long term creep (sackungen). They are an extremely efficient way of linking hillslopes to rivers and relieving the landscape of tectonic derived stress. It is becoming clear that rock avalanches are responsible for large proportions of mountain erosion and have significant effects on other landscape formational processes. During emplacement rock avalanches thoroughly fragment to leave a deposit composed of predominantly sand and gravel grades, material that should be readily transported by most major mountain river systems. A complication at this stage is added by the common formation of landslide dams by rock-avalanche debris, delaying for a period of several days to millennia the dispersal of this fragmented debris. The timing of the failure of such dams results in an interruption to the evolution of the mountain landscape and valley-fill over varied spatial and temporal scales, and a geomorphic imprint that may extend into the geological record and affect landscape evolution at regional scales. The geomorphic signature of this interruption and the subsequent dispersal of rock-avalanche debris is a key issue for both hillslope and river processes with as yet un-quantified feedbacks and links to ongoing tectonics.

Keywords. Landslide, physical modelling, cellular modelling, hillslope coupling

1. Introduction

In tectonically active mountain belts catastrophic landslides are an extremely efficient mechanism of delivering large quantities of sediment to river networks. Onsite impacts of the delivery of material can range from near immediate dispersal of the input, a long-lasting point sediment source, to a full blockage as a landslide dam of uncertain persistence that can be measured in days to millennia. Much research has focussed on these immediate aspects of the coupling between landslides and the drainage network for hazard and risk (Dunning et al. 2006, 2007). More recently researchers have tried to integrate state-of-the-art fluvial geomorphology and hillslope science over a diverse range of temporal and spatial scales (for example Korup, 2005, Hewitt 2006). The key limitation for such studies is usually the timescales of interest when considering the impacts such landslide-river coupling has on the landscape. Traditionally the techniques of choice either substitute space for time and attempt to link a sequence of 'process snapshots' to provide a reasoned and coherent model of landscape response; or, use highly dynamic landscapes where the geomorphic lag-time is measured in

Fig. 1 Chronic supply of debris altering a landscape for an as yet unknown period of time, the 2005 Hattian Bala rock avalanche deposit.

years to decades. A good example of the first method is the 'Disturbance regime landscape' model of Hewitt (2006) that focuses on rock-avalanche deposits. Rock avalanches are a high magnitude, low frequency catastrophic landslide that are particularly effective at blocking rivers due to the mechanism of emplacement and volume of debris (Fig 1). During emplacement rock avalanche debris is fragmented into a fractal mixture of gravel and sand (Dunning 2006), so although initially forming an efficient dam with important upstream and downstream geomorphic consequences, upon breaching much of the deposit is removed through subsequent river action. It is often the geomorphic response of the landscape that persists rather than the original in-situ landslide debris. These geomorphic responses are in themselves often transitory, and often linked to multiple blockages along a river profile, hence the delimitation of a series of broad stages of landscape response in the model of Hewitt (2006).

Utilising the rapid geomorphic and tectonic rates in New Zealand has enabled Korup (2004, 2005, 2006) to assess the impact of either pulsed (Fig. 2) or chronic (Fig. 1) supplies of landslide debris to river networks. On a short timescale (years to decades) landslide-debris coupled with valley floors has resulted in alterations to river long profiles; forced avulsions, catastrophic aggradation and degradation as a series of sediment pulses, and perhaps most importantly has shown that these processes exceed background trends by an order of magnitude.

Based on the studies briefly outlined above, the immediate question that arises is: 'If landscapes and fluvial systems in tectonically active terrain are frequently perturbed by large landslides can they ever achieve 'steady state'?'

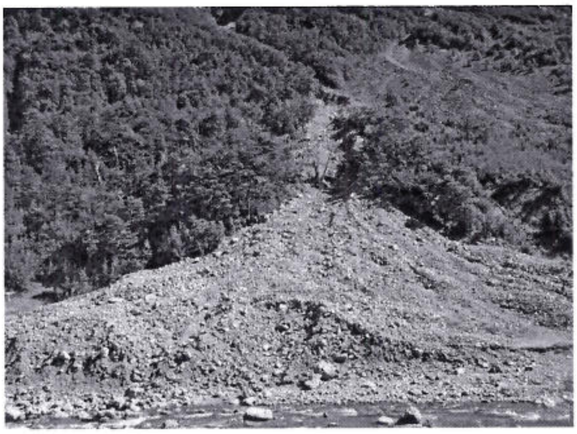

Fig. 2 Pulsed supply of debris being fed into a river able to sluice the toe and disperse the material downstream, Edwards River, New Zealand.

where steady state is a temporally invariant topography, a balance between uplift and erosion. Within this, bedrock or the more commonly observed mixed bedrock-alluvial rivers must transport all of the sediment being supplied from upstream, and also incise its bed at a rate equal to the tectonic uplift (Whipple and Tucker, 2002). With the large number of known events, both chronic and pulsed that exceed 'background rates of delivery', and their interpreted return periods it can be seen that the inputs can have fundamental effects on regional scales in the short term of years to decades and may persist geomorphically for millennia. It is within this framework that equipment has been commissioned to investigate the spatial and temporal impact of chronic and pulsed hillslope-river coupled debris as it is dispersed through the landscape.

2. Proposed methodology

To gain insight into the geomorphic response to landslide debris dispersion two methods are being utilised, microscale hydraulic modelling (herein termed MSM) and numeric cellular modelling, both to be backed with field studies for prototyping and verification.

2.1 Microscale hydraulic modelling (MSM)

Physical modelling has developed alongside mathematical approaches to understand the complex relationships between the production and transport of sediment under the influence of water. Physical models have the benefit of allowing the formation and destruction of fluvial features as a continuous process usually impossible to constrain using field investigation alone.

Hydraulic modelling is suitable to investigate a range of problems and takes a number of forms dependent upon the similarity to the prototype system required, be it a specific prototype or a generic class of geomorphic feature. The choice of modelling technique is a balance between model specificity and the scale of interest, both spatially and temporally (Peakall et al. 1996). The models offering the best replication of natural systems are 1:1 models, often used for fluvial bedforms, however, this is clearly unsuitable for the scales of interest in this study and it is more usual to compromise specificity and distort scaling. This study utilises microscale modelling, or analogue modelling, the least representative of the prototype but retaining many important geomorphic similarities that can be used to test large-scale dynamics of complex, slowly evolving geomorphic settings, or rapid systems where time needs to be compressed, things currently difficult to achieve by other means (Schumm et al. 1987, Peakall et al. 1996). Famous analogues for this approach include Stanley Schumm who '...once refused to let his daughters eat a bowl of chocolate pudding for two days, because, as it desiccated, fractures that resembled lunar features were forming on its surface' (Schumm et al. 1987, p. 1). MSM reproduces significant aspects of the form of the fluvial system, in this case the morphologic characteristics using the ideas of 'similarity of process' (Hooke, 1968, in Schumm, 1987). The real problems lie in trying to upscale these models and delimit rates of evolution, as well as the variability of natural system variability and inputs.

With these issues in mind, MSM is a useful methodology and has produced successes that directly relate to this work, notably, studies of river aggradation, (Davies et al. 2003), fanhead trenching due to landslide debris inputs (Davies and Korup, 2007), and the incision of bedrock rivers in response to bedload supply (Finnegan et al. 2007).

The MSM modelling equipment in use has been constructed by Lincoln University, with scientific input from Canterbury University, New Zealand. The model is a 5 m x 2 m system in three modules designed so that differential subsidence / uplift can be included within model runs. Water is supplied at up to 3 l/min and sediment up to 200 g/min. What makes the model different from many is the inclusion of an overhead rainfall simulator capable of 20-60 mm/hr rates usually used for channel initiation studies. This allows the driving of hillslope-river coupling using forcing factors other than river incision and hillslope steepening / hillslope lengthening. It also has the benefit of allowing comparison of the effects of landslide blockages and landslide sediment supply on the processes above and below input sites. In the case of a conventional model of a landslide dam, no drivers of change are active below the dam site once the pumped water is stopped by the dam debris. DEMs are derived using a combination of laser scanning and white light photogrammetric techniques.

Numerous scaling issues are present in this combination of model types but morphologic similarity still holds across the model as a fully functional landsystem in own right and as an analogue to the natural system. Fine silica sand is used for the alluvial component and can form the entirety of the model or be used with a bedrock substitute, a mixture of cement, fine sand, fly ash and a flow additive (Finnegan et al. 2007) or fine sand / kaolinite mixture (Schumm et al. 1987). These bedrock substitutes can be eroded using the supply of sand as tools and has proven success in fluvial modelling.

2.2 Numerical modelling

A numerical modelling approach has been chosen as complimentory method to investigate the impact of landslide derived sediment on hillslope and fluvial systems. The code of choice, CAESAR (see Van De Wiel et al. 2007) has considerable success in simulating the reach and catchment scale alluvial dynamics within a landscape evolution model. CAESAR is a cellular automaton model that follows a set of

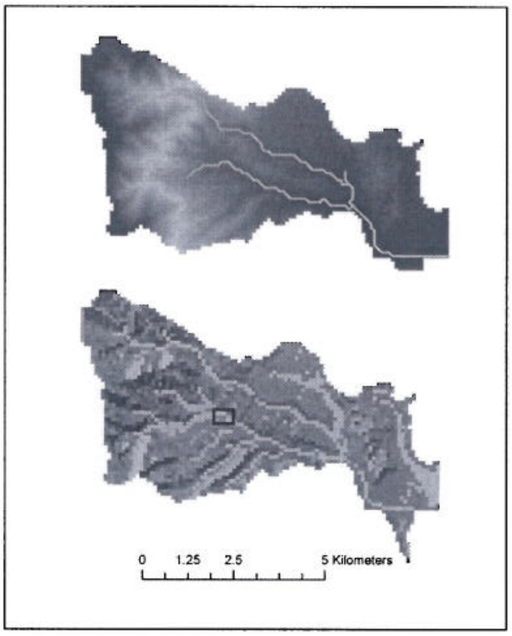

Fig. 3 (Upper) Shaded DEM of Ram Creek catchment with only the rivers draining the upland area of interest marked (Lower) Example output of CAESAR model showing the routing of a severe rainfall/flood event through the catchment, note the backwater effect due to the presence of the remnant landslide dam (square). The DEM has been rotated 180° for model convention.

rules designed to represent fluvial and hillslope processes. These rules are necessarily simplifications but when iterated allow complex non-linear geomorphic behaviour and feedbacks similar to natural systems (Fig. 3). The replication of channel incision, bed armouring, lateral migration, terrace formation, and vertical stratigraphy development are the most important model outputs for this study. The ability of the model to simulate both meandering and braided behaviour is key, in many instances the input of catastrophic landslide debris triggers the change from one to the other as the sediment disperses. The models simplicity requires few inputs, useful when hydraulic model inputs are often exceptionally difficult to quantify for the systems of interest. Required are a DEM, grain sizes for the grid, and vegetation parameters. The topography drives fluvial and hillslope processes to alter the landscape by erosion and deposition. The forcing factor can be rainfall data (actual or calculated) for a drainage basin mode, or discharge and sediment fluxes for a reach mode. In addition CAESAR can model the point source input of a defined sediment of interest, the equivalent of adding coloured sand to the physical model. This feature allows the tracing of the fate of landslide debris imputed (chronically or pulsed) into the system, be it initially coupled to the fluvial network or not and so constrain the dispersion and impact of the debris to river planform and the landscape.

3. Selected prototypes

The methods outlined above, in combination with field study allow for investigation of the role landslide debris plays in altering river geomorphology, and through this, potentially alter the response of landscape to the driving tectonic when compared to catchments without landslide inputs. Initially prototypes of both chronic and pulsed sediment supply in a region of high geomorphic activity are being investigated to allow the maximum chance for model verification. One example prototype of a rock avalanche dam deposit is outlined here.

3.1 Ram Creek, New Zealand

The Ram Creek rock avalanche was triggered by the 1968 Inangahua Earthquake (M 7.2) and involved around 4.4 x 10^6 m^3 (Nash, 2003) of granitic bedrock. The material dammed the small tributary ~ 6 km upstream of the major Buller River. The drainage basin above the dam site was comparatively small and the resultant landslide dammed lake took 13 years to overtop after a period of stable inflow / seepage outflow. When overtopping took place, it was catastrophic and the resulting breach released 1 x10^6 m^3 of water and a similar amount of debris. Field investigation of the remnant landslide debris not mobilised during the outburst supports the interpretation of a rock avalanche type mass movement, the interior of the mass is highly fragmented (D_{50}

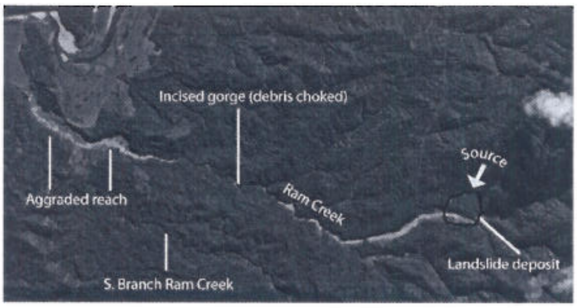

Fig. 4 Overview of Ram Creek deposit and downstream dispersal of debris since 1981 breach. Field of view is ~ 6km. Background image © DigitalGlobe courtesy of GoogleEarth Pro.

as measured by Nash (2003) is 70 mm). It is estimated from regression equations that the flood wave peaked at around 1000 m^3s^{-1} in Ram Creek, resulting in the equivalent to an annual flood in the gauged Buller River downstream (4335 m^3s^{-1}). Debris was deposited over a length of ~5.5 km below the dam site though most of the debris stalled immediately downstream of the breach (Fig. 4).

The original dispersion of this chronic supply of over 1 x 10^6 m^6 of material to the fluvial system is an interesting model prototype as it is estimated that a 2m depth of debris was deposited over 250,000 m^2 of land during several pulses of flood flow (Ben, 1990, in Nash, 2003). The future fate of this amount of sediment in a small (13 km^2) mountain catchment is a problem ideally scaled to the methods presented. The upsteam section of Ram Creek is an incised gorge (Fig. 5) typical of the west coast of New Zealand than opens out downstream into the Buller River (Fig. 4). Of interest is the reaction of Ram Creek to the immediate armouring of the gorge base and the subsequent alteration to incision and the downstream sedimentation and planform as the channel opens

Fig. 5 View of the lower gorge section of Ram Creek with the landslide outburst flood sediment.

out, currently showing large scale aggradation. An additional factor suited to the physical modelling is that Ram Creek crosses the Lyell Fault below the dam site, interpreted to have been reactivated during the 1968 earthquake with downthrow to the west (Yeats, 2000).

3. Conclusions

Two methodologies have been presented to investigate the role that coupled hillslope-river landslide debris may have on the geomorphology of mountainous systems. The main problems encountered are validation and upscaling, essentially a model is being used to validate a model with great difficulty in testing prototype response due to the timescales involved. The methods rely on gross simplification of natural systems, but both retain similarity of geomorphic response and have proven success individually.

An initial set of models does not use CAESAR to test prototype DEMs against MSM modelling, it is applicable to treat the MSM model as a very controlled landsystem in its own right and use DEMs and rainfall / discharges derived directly from the model to test geomorphic response. This calibration of the numerical model against the physical model allows assessment of variation of MSM behaviour against actual DEM response in the CAESAR model and is the first step to upscaling results from both methods and allowing comparison against conceptual models of landscape response to landslide interruptions.

Acknowledgments

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